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Calculating the Level of Noise Generated by Steam Jets Discharged into the Atmosphere at Thermal Power Stations

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Abstract—The specific features pertinent to the jets produced when steam is discharged into the atmosphere at thermal power stations are considered, and the noise generated by such jets is analyzed. A method for calculating the outflow of steam jets is proposed that uses the theory of jets having a high inefficiency ratio, and a formula for determining the overall level of acoustic power generated by a steam discharge is suggested, the parameters of which are related to the jet isobaric section.

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Discharges of steam into the atmosphere are an integral part of the technological process at thermal power stations (TPSs); these operations are usually carried out when the kindling of boilers is in progress, when the main safety valves are opened in emergency or forced manner, when steam superheaters are purged, etc. [1].

If we wish to calculate the level of noise at certain distance from the location where steam is discharged and to develop measures for noise suppression, we must study the outflow of steam jets into the atmosphere.

Calculations for determining the level of noise generated by steam discharges have hitherto been carried out without taking into account the fundamental features pertinent to the outflow of steam jets into the atmosphere. Existing methods for determining the total level of the acoustic power are based on adding empirical corrections to the formulas for calculating the level of noise from the jet engines of planes [2], the noise generated by an air jet [2, 3], or using only the empirical data [4]. In [5], existing approaches and correlations used for determining noise level are compared, and it is shown using the results from this comparison that the existing formulas for calculating steam jets give a considerable error, that the procedure of preparing initial data is rather labor consuming, and that the most accurate equation has a limited application range: the jet inefficiency ratio n = 4.6–9.9. In order to overcome these drawbacks, we developed a method for calculating the level of noise generated by a steam jet using the theory of jets having a high inefficiency ratio. It is the first time that this theory has been used in application to the features characteristic of steam discharges at TPSs. Our tests have shown that the outflow of steam jets entails the occurrence of a hanging compression shock, a Mach disk, and a zone of intensive mixing downstream of it (Fig. 1). The level of noise generated by such steam jets can be calculated using the theory of jets having a high inefficiency ratio [6]. In accordance with this theory, a system of expansion and compression waves, as well as the compression shocks, occurs in the jet section adjacent to the pipeline outlet; it owing to these waves and jumps that the pressures in the jets are gradually equalized with those in the surrounding medium. A barrel-shaped section appears at the initial part of the jet (clearly seen in Fig. 1), in which huge pressure drops occur; the pressure downstream of this barrel-shaped section is almost equal to the atmospheric pressure, and, consequently, the jet becomes isobaric in nature [6].

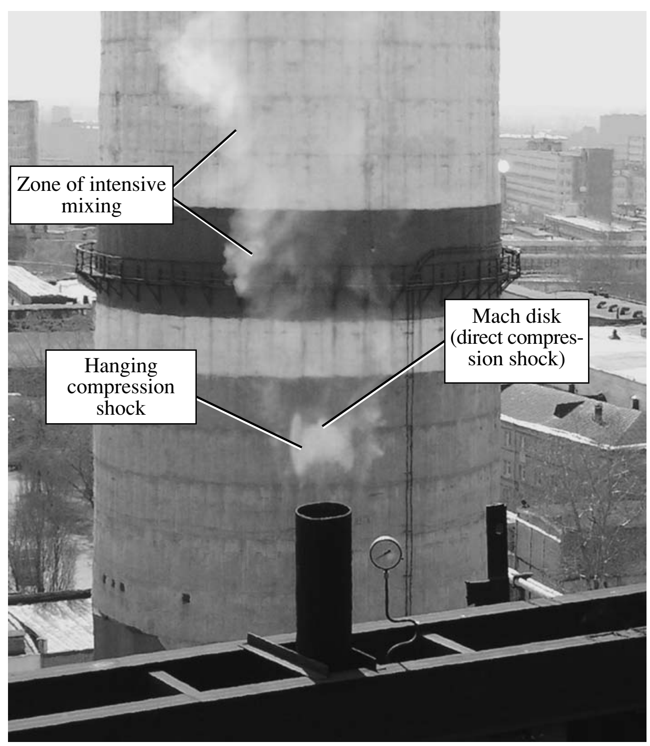

Fig. 1. Photograph of the steam jet having inefficiency ratio n = 3.8, temperature t = 400°C, and critical velocity u_{cr} = 631.4 m/s.

A simple theory based on representing a flow by means of a single-dimensional model has received practical use to construct the pattern of current in an incompletely expanded jet [6]. Although the fields of velocities and pressures found in cross sections of an inefficient jet are essentially nonuniform, the principles of this theory can be used to obtain an idea about the true dimensions and shape such a jet has in its initial part. The calculation method proposed in [6] is based on averaging the parameters of a jet over its cross section and approximating it as a single-dimensional gas flow. The mixing of steam with the air of the immobile surrounding medium in the initial section is ignored, but this does not introduce considerable errors into the calculation results [6]. The system of equations used to calculate the jet includes those for conservation of energy, continuity, and momentum, the solution of which allows one to correctly estimate almost all the main properties of a flow represented by a single-dimensional model. This method is used to determine a certain flow cross section in which the parameters reach their constant values provided that there is no mixing with the external medium. The static pressure found at this section, which is called an isobaric, is equal to the external pressure; as a result, no further changes occur in the parameters of the flow. The jet observed at the isobaric section remains supersonic: the transition through the sound velocity becomes possible only as a result of jet being mixed with the external medium, a phenomenon that is not taken into account.

A jet generates noise as a result of gas particles mixing—in a large- and small-scale turbulent manner and with a velocity close to the outflow one—with the particles of the surrounding gas [7]. It is then reasonable to consider that noise does not occur in the jet section from the pipeline edge to the isobaric section. Thus, if we wish to calculate the acoustic power P of a steam jet, we must use the parameters at the isobaric section and not at the nozzle outlet, as was done hitherto; the calculation formula obtained using Lighthill's theory has the form [8]:

$$P = K(\lambda)\rho_{\text{out}}^2 u_{\text{out}}^8 D_{\text{out}}^2/[\rho_0(c_0)^5], \tag{1}$$

where $K(\lambda)$ is a proportionality factor determined from the results of experiments, ρ_{out} is the density of steam in the jet, u_{out} is its outflow velocity, D_{out} is the jet diameter, λ is the relative velocity, ρ is the density of the surrounding medium, and c_0 is the velocity of sound in the surrounding medium.

The value of $K(\lambda)$ was determined from the results of acoustic pressure measurements, which were carried out using a noise spectrum frequency analyzer (produced by Larson Davis Laboratories). This instrument allows the levels of acoustic pressure to be determined simultaneously in the octave (31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000, and 16000 Hz) and third-octave (25–10 000 Hz) bands of geometric mean frequencies; it also allows maximum, minimum, and peak values of acoustic pressure and sound levels to be recorded. The measurement error is ±0.1 dB.

The proportionality coefficient is given by

$$K(\lambda) = 10^{-(1.85\lambda + 2.01)}. \tag{2}$$

The jet outflow velocity is given by [6]

$$u_{\text{out}} = u_{\text{cr}}\lambda, \tag{3}$$

where u_{cr} is the critical velocity of steam at the outlet from the exhaust or blowdown pipeline;

$$\lambda = \frac{G_0}{G_{\text{out}}}\left[1 + \lambda_0^2 - \frac{1}{n}\left(1 - \frac{k-1}{k+1}\lambda_0^2\right)\right]\frac{k+1}{2k\lambda_0}, \tag{4}$$

where $G_0/G_{\text{out}} = 1$ is the ratio of the steam flowrate at the outlet from the pipeline to that at the isobaric cross section; $\lambda_0 = 1$ is the ratio of the jet outflow velocity at the pipe outlet to the velocity of sound in it; $k = 1.3$ is the adiabatic index for superheated steam; and n is the jet inefficiency ratio, which is defined as the ratio of the critical steam pressure at the pipeline outlet p_{cr} to the atmospheric pressure p_{at}.

The area of the jet's isobaric cross-section is given by

$$S_{\text{out}} = S_{\text{p}}\frac{G_{\text{out}}}{G_0}\frac{\lambda_0}{\lambda}\frac{1 - \dfrac{k-1}{k+1}\lambda^2}{1 - \dfrac{k-1}{k+1}\lambda_0^2}n, \tag{5}$$

where S_{p} is the outlet cross-section area of the blowdown or exhaust pipeline.

The density of steam at the isobaric section is determined from the continuity equation

$$\rho_{\text{out}} = G_{\text{out}}/(S_{\text{out}}u_{\text{out}}). \tag{6}$$

The critical pressure of steam at the pipeline outlet, Pa, can be found using the following expression [9]:

$$p_{\text{cr}} = \frac{m_{\text{cr}}\sqrt{2k/(k+1)\rho_0 v_0}}{k}, \tag{7}$$

where $m_{\text{cr}} = G_0/S_{\text{p}}$ is the mass velocity for the critical jet outflow, kg/(m^2 s), and v_0 and p_0 are the specific volume of steam and its pressure when its velocity is close to zero.

The critical flow velocity u_{cr} (sound), m/s, of a jet of steam (gas) is calculated using the formula

$$u_{\text{cr}} = \sqrt{2k/(k+1)\rho_0 v_0}, \tag{8}$$

and its inefficiency ratio, using the expression

$$n = u_{\text{cr}}G_0/(kS_{\text{p}}p_{\text{at}}). \tag{9}$$

Since the critical velocity u_{cr} of a jet resulting from discharges of steam having a temperature of 400–450°C and pressure of 0.196–5.737 MPa (2.0–58.5 kgf/cm^2) varies over a narrow range from 609.5 to 658.1 m/s [10], the mean value of u_{cr} = 633.8 m/s is used, which allows the calculations to be greatly simplified. The maximum error introduced by such an approximation is within ±0.5 dB.

Substituting expressions (2), (3), (5), and (6) into (1) and making the necessary mathematical rearrangement, we come to the following formula for calculating the overall level of acoustic pressure L_P generated by a steam discharge:

$$L_P = 10 \times \log\left(\frac{G_0^2}{S_p}\right) + 10 \times \log\left(\frac{\lambda^7}{(1-0.13\lambda^2)n}\right) - 18.5\lambda + 141.3. \quad (10)$$

To check the results obtained, we arranged different steam discharge regimes, in which acoustic measurements were carried out in accordance with the well-known procedure (see table). In Fig. 2 we find a comparison between the calculated and measured values of noise from the exhaust pipeline (having an inner diameter of 0.257 m) and the blowdown pipeline (having an inner diameter of 0.101 m), both carrying divergent flows; the calculated data are in satisfactory agreement with the measured data.

Parameters of the discharged steam obtained from acoustic measurements 15 m from the discharge location

Exhaust pipeline

Parameter	No. of regime		
	1	2	3
Steam in the boiler:			
pressure, MPa (kg/cm^2)	5.2(53)	9.6(98)	12.9(132)
temperature, °C	488	530	538
Parameters of steam being discharged:			
flowrate, kg/s	16.1	29.3	39.5
temperature, °C	381	390	390
inefficiency ratio	1.5	2.8	3.9
Overall level of acoustic power L_P, dB	161.0	165.3	167.2

Blowdown pipeline

Steam in the boiler:	
pressure, MPa (kgf/cm^2)	13.0 (133)
temperature, °C	550
Discharged steam:	
flowrate, kg/s	21.4 × 2
temperature, °C	409
inefficiency ratio	13.3
Overall level of acoustic power L_P, dB	167.3

Hence, formula (10) can be used to determine the overall level of acoustic power generated by a steam discharge at a TPS for the inefficiency ratio n ranging from 1.5 to 13.3. This range is much wider than that in other well-known formulas [5] for calculating the acoustic power generated by a steam jet.

In practice, it is recommended to use the data in [5] for determining the levels of acoustic pressure in the octave bands with standardized geometric mean frequencies at the specified distance from the steam discharge.

Thus, an expression has been obtained for calculating the overall level of acoustic pressure generated by a steam discharge; the parameters of this expression are related to the jet's isobaric section. The expression has been experimentally checked for steam jets with inefficiency ratios ranging from 1.5 to 13.3.

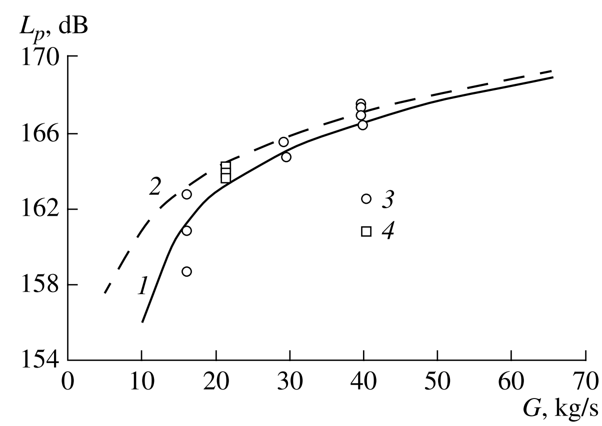

Fig. 2. Comparison between the noise levels calculated using formula (10) (curves *1* and *2*) and the measurement results (curves *3* and *4*). Pipelines: *1* and *3* are for the exhaust pipeline, and *2* and *4* are for the blowdown pipeline.

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